2×2 Exchange/Bypass Switch Using 0.8 m of Highly Nonlinear Bismuth Oxide Fiber

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***Abstract*—We demonstrate an optically controlled 2×2 exchange/bypass switch using 0.8 m of highly nonlinear bismuth oxide fiber in an ultrafast-nonlinear-interferometer configuration. The switch has operated error-free with 10- and 40-Gb/s input signals, with power penalties in its BYPASS and EXCHANGE states of less than 0.3 and 1 dB, respectively. Use of the short bismuth oxide fiber ensured compact size, small latency, and improved operational stability compared to previous fiber-based switches.**

***Index Terms*—All-optical signal processing, bismuth oxide nonlinear fiber (Bi-NLF), crossbar switch, optically controlled exchange/bypass switch, ultrafast nonlinear interferometer (UNI).**

I. Introduction

ALL-OPTICAL signal processing devices, circuits, and subsystems have relied for their nonlinearity either on carrier-induced ultrafast refractive index changes in semiconductors or on the femtosecond, Kerr-effect in optical fibers. So far, all-optical semiconductor devices have offered significant advantages as they combine high nonlinearity with compact size and capability for integration. Nonlinear fibers provide the unique advantages of femtosecond nonlinearity response, nearly penalty-free switching, and operation without electrical power supply. However, the low nonlinearity of conventional dispersion-shifted fibers has required the use of bulky kilometer-length spans that have rendered fiber-based switches impractical, especially for multigate applications. In those implementations, switch size was mainly determined by the long fiber spools employed, highlighting the need for more sophisticated nonlinear fibers. Recent advances in the fabrication of low-loss, highly nonlinear fibers (HNLF) have reactivated interest in fiber-based devices [1]. One of the most interesting HNLF types which has recently attracted significant attention is bismuth oxide (Bi_2O_3)-based nonlinear fiber (Bi-NLF). Bi-NLF nonlinearity is much higher than other nonlinear fibers [1] and exceeds 1000 $W^{-1} \cdot km^{-1}$[2], hence, fiber lengths in the order of 1 m may be used [3], [4], resulting in all-optical fiber switches of much more compact size compared to previous fiber-based implementations (see [3] and its references). Besides enhanced compactness, the dramatically reduced fiber length provides a significant reduction of switch latency. Even though switch latency is not an issue in feed-forward applications such as demultiplexing or regeneration, it may be crucial in signal processing circuits that use feedback designs.

In this letter, we use 0.8 m of highly nonlinear Bi-NLF to implement an optically controlled 2×2 exchange/bypass switch. The switch is based on a single-arm ultrafast nonlinear interferometer (UNI) gate [5], which uses the 0.8-m-long Bi-NLF as the nonlinear interaction medium in order to obtain a complete π phase shift. The below 200-fs nonlinearity response time [6] ensures that the switching window is defined by the width of the control pulses. This has enabled bitwise operation at input data rates of 40 Gb/s and at least in principle the operation of the scheme could be extended to significantly higher data rates. Error-free operation has been achieved with power penalties in its BYPASS and EXCHANGE states of less than 0.3 and 1 dB, respectively. A low latency 2×2 exchange-bypass switch is a key unit for the implementation of a full range of circuits including switching matrices [7], adders [8], header reinsertion circuits [9], time-slot interchangers [10] and synchronization stages [11], optical buffers [11], pseudorandom binary sequence (PRBS) generators, and data scramblers.

II. Experimental Setup

Fig. 1 shows the experimental setup used for the evaluation of the 2×2 exchange/bypass switch. A 1553-nm distributed feedback (DFB) laser diode was gain switched at 10 GHz to generate 10-ps pulses. These pulses were compressed to 3 ps in a nonlinear fiber pulse compressor and were then modulated with a Ti:$LiNbO_3$ modulator (MOD1) to form a pseudorandom data pattern. The signal was subsequently split in a 3-dB coupler into two parts: The first part entered an all-optical wavelength converter consisting of an integrated, semiconductor Mach–Zehnder interferometer (MZI 1) to generate a 10-Gb/s input signal at 1558 nm (IN 1). The second part was introduced into a fiber bit interleaver to form a 40-Gb/s $2^7 - 1$ PRBS data pattern (IN 2). The control signal was provided by another 10-GHz gain switched laser (DFB 2) operating at 1534 nm and producing 8.2-ps clock pulses. These pulses were modulated in a Ti:$LiNbO_3$ modulator (MOD2) to produce bursts of clock pulses with 2.3-ns duration and 40.5-ns period and were amplified in a high-power erbium-doped fiber amplifier. These three signals were injected into the 2×2 exchange/bypass switch which was implemented with a 2-input, 2-output UNI gate, as shown in Fig. 1. The nonlinear element in the UNI was a 0.8-m-long highly nonlinear ($\gamma = 950$ $W^{-1} \cdot km^{-1}$) Bi-NLF with 2-μm core diameter, which was pigtailed with single-mode fiber (SMF). The Bi-NLF exhibited 1.3-dB/m

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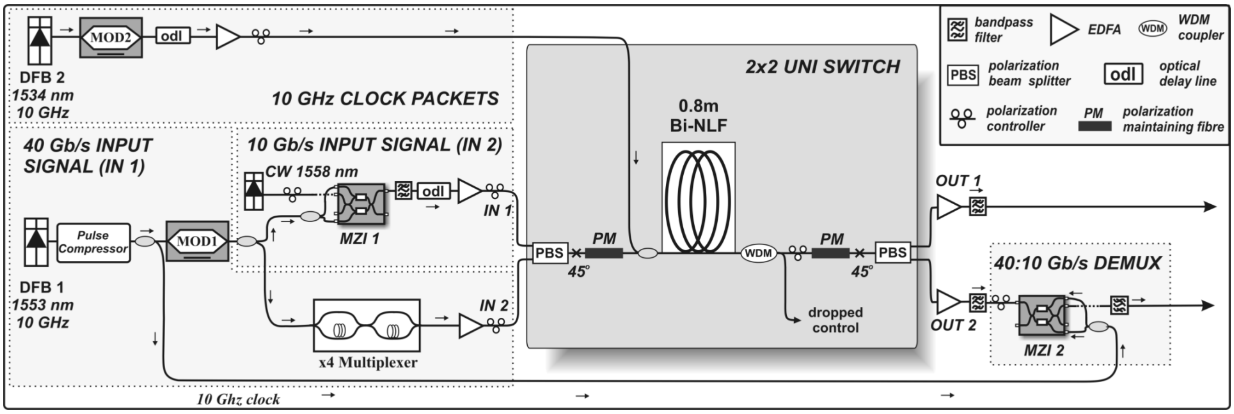

Fig. 1. Experimental setup.

propagation losses whereas the input pigtail splice introduced an additional 2.1-dB loss. The UNI switch is described in [12] and in our setup it was configured to operate with two inputs as follows. The time-synchronized input signals entered the switch in orthogonal polarizations from the ordinary and extraordinary ports of a polarization beam splitter (PBS) respectively. A 45° splice analyzed each signal in two equal components which propagated along the fast and slow axis of the subsequent polarization-maintaining (PM) fiber section respectively. The PM section provided 10 ps of birefringent delay in order to temporally separate the fast and slow component of each signal before the Bi-NLF. The control signal was launched into the switch through a 90 : 10 fiber coupler so that it cotravels with the input signals. Fine bitwise synchronization between the three optical signals was achieved with two optical delay lines, so that the control pulse coincided with the trailing component of both input signals. After interaction in the Bi-NLF, the control signal was removed with a 1550/1530-nm wavelength selective coupler. Re-alignment of the input signals was obtained by another PM section with equal birefringence, where the fast/slow signal components were aligned to the slow/fast PM fiber axis, respectively, by means of a polarization controller. A 45° splice followed by a PBS perform spatial separation of the resultant signals at the corresponding PBS outputs according to their polarization state. In the absence of the control signal, data signal IN 1 passes through to OUT 1 and data signal IN 2 passes through to OUT 2. In the presence of the control signal, the polarization state of each input data component which temporally coincides with the control is rotated by 90°. As a result, the 10-Gb/s channel of IN 1 and the synchronized 10-Gb/s data channel of IN 2 are interchanged at the outputs of the switch. Component pigtails added 6 m of SMF length to our 2×2 switch, which induced negligible differential group-delay (0.015 ps). Hence, SMF birefringence does not limit switch operation at ultrahigh bitrates. Finally, bit-error-rate (BER) measurements were performed at both outputs of the switch. The BER performance of the 40-Gb/s signal of OUT 2 was assessed with a 40- to 10-Gb/s data-demultiplexer, so as to evaluate each of the 10-Gb/s tributary channels. Demultiplexing was performed with a second integrated Mach–Zehnder interferometer (MZI 2) operating in push–pull control configuration with 3-ps clock pulses at 1553 nm.

III. Results and Discussion

The experimental results of the 2×2 exchange/bypass switch are illustrated in Fig. 2, showing both oscilloscope traces and eye diagrams. The top rows depict BYPASS state operation of the switch whereas the bottom rows show the EXCHANGE state along with the respective control signal. The 2×2 switching occurs throughout the entire time window shown in Fig. 2, which is shorter than the burst length. The corresponding eye diagrams demonstrate an extinction ratio of approximately 10.1 dB for OUT 1 and 11 dB for OUT 2 in BYPASS state operation. For the EXCHANGE state, the extinction ratio was 9.5 dB for OUT 1 and 10 dB for OUT 2.

The BER performance of the switch is displayed in Fig. 3. BER curves are presented for the 10-Gb/s signals of IN 1 and OUT 1 along with the corresponding 10-Gb/s data channels of IN 2 and OUT 2 for both BYPASS and EXCHANGE states. Error-free 2×2 operation was achieved in both BYPASS and EXCHANGE states with low power penalties. In BYPASS state operation, a power penalty of 0.3 and 0.28 dB was obtained for OUT 1 and OUT 2 ports, respectively. EXCHANGE state operation introduced a power penalty of 0.8 and 1.06 dB for OUT 1 and OUT 2 ports. For this operation, the peak power of the control pulses was 8.5 W, corresponding to 69.7-pJ pulse energy and a complete π nonlinear phase change. These power levels refer to the input of the the Bi-NLF fiber and exclude the splice losses between the SMF pigtail and the Bi-NLF fiber. The additional 2-dB power penalty at the input 10-Gb/s signal (IN 1) compared to the input 40 Gb/s (IN 2) is due to the wavelength conversion in MZI 1. The polarization of both input signals was adjusted so as to maximize power transmitted through the input PBS, whereas control signal polarization was set with view to optimum switching. Once all polarizations were adjusted, the switch remained untouched during the collection of the experimental results, for a time period of approximately 1 h. Stable switch operation is attributed to the ultrashort Bi-NLF spool which allowed for very short overall switch length. The interacting signals were synchronized at the Bi-NLF input, whereas their walkoff at the fiber output was in the order of 1 ps for the two input signals and 6 ps for IN 2 and the control signal, thus enabling switch operation at 40 Gb/s and beyond. Small signal walkoff was obtained despite high fiber dispersion (-270 ps/nm/km) due to the ultrashort length of the Bi-NLF.

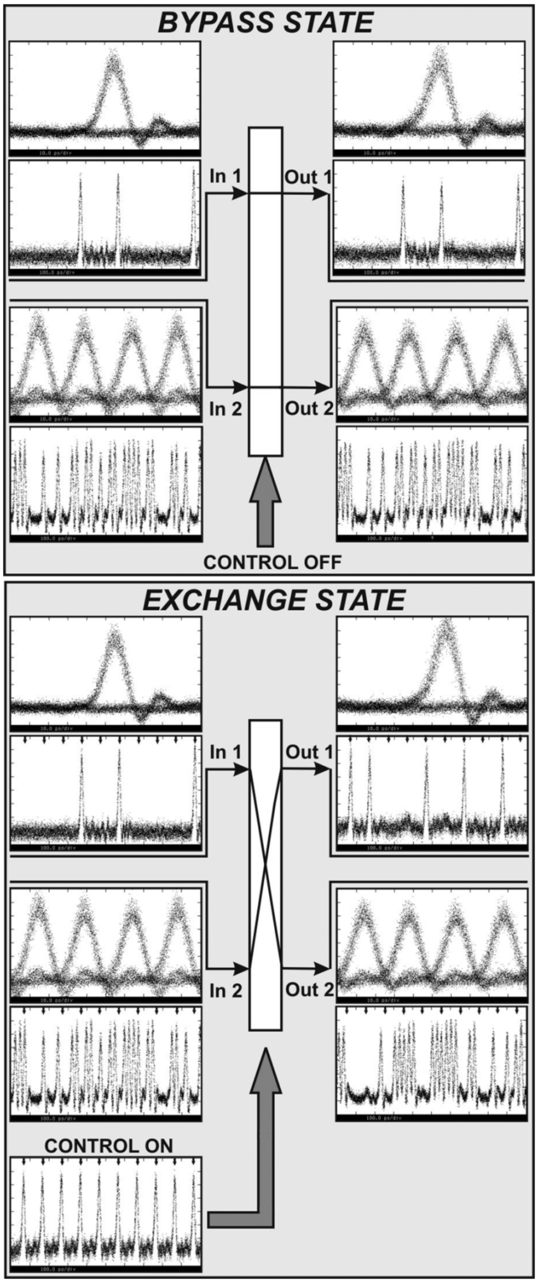

Fig. 2. Oscilloscope traces and respective eye diagrams in the BYPASS and EXCHANGE states. First column: BYPASS state operation. Second column: EXCHANGE state operation. The time base is 100 ps/div for the oscilloscope traces and 10 ps/div for the eye diagrams. Arrows indicate the time slots which coincide with the control pulses.

IV. Conclusion

We have demonstrated an optically controlled a 2×2 exchange/bypass switch using only 0.8 m of highly nonlinear bismuth oxide fiber in an UNI configuration. The short length of the Bi-NLF fiber provides compact size compared to previous fiber-based implementations, enhances polarization stability, and allows for small latency of the device. Error-free 2×2 operation was demonstrated with both 10- and 40-Gb/s signals and low power penalties were obtained, indicating the switch may be cascaded or used in feedback applications, without requiring regeneration.

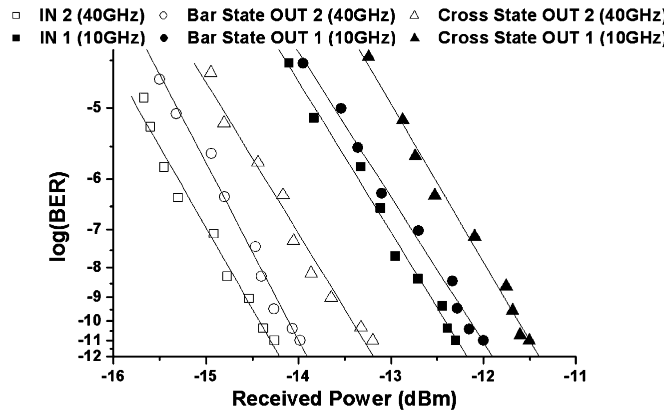

Fig. 3. BER measurements in BYPASS and EXCHANGE states.

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